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Progress toward ignition with non-cryogenic double-shell capsules

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Experimental observations of inertial confinement fusion (ICF) implosions using capsules with two concentric shells separated by a low density region (double-shells) are reported. The results using capsule designs which mitigate the Au M-band radiation asymmetries, closely follow one-dimensional radiatively driven hydrodynamic simulations. One of our capsule designs achieves over 90% of the 1D calculated neutron yield at a convergence ratio comparable to that of a double-shell design for an ignition capsule at the National Ignition Facility. In this paper, we discuss recent experimental results using double shell targets mounted in cylindrical hohlraums at the Omega Laser Facility. These recent experiments have produced substantially equivalent results to those using spherical hohlraums with four laser entrance holes in our earlier experiments (Varnum et. al. ,2000). Observed neutron yield of 50% to 100% of 1D calculation was seen in a number of shots with convergence ratio up to 38. Imploded core images and neutron yield (measured versus calculated) are discussed in detail for the recent experiments.

1. Introduction

Double shell capsules have been ignored for a number of years because it was assumed that they would be too hydrodynamically unstable to reach ignition and high gain at the low energies available from laboratory facilities. Because recent calculations indicate that double shell targets may provide an alternative non cryogenic path to ignition on NIF, experiments have been conducted at the Omega laser facility to study indirectly driven double shell implosions. The goal of our double shell experimental campaign is to assess the viability of a potential non cryogenic implosion target for ignition applications at NIF. The double shell design is a room temperature target capable of holding enough gas to ignite in a Au inner shell driven in a staged manner by the collision of an outer Cu-Be shell onto the inner Au shell. In contrast to the standard single shell NIF point design target, the NIF double shell target removes the need for cryogenic manipulation and requires a relatively simpler 6 ns square laser pulse instead of a longer, complicated shaped pulse. A NIF double shell design operates at a convergence of about 32 and produces gain of order ~1 with a 300 TW, 6 ns square laser pulse.

The most important reason for studying double shell capsules, apart from the noncryogenic aspect, is the issue of velocity multiplication in the implosion hydrodynamics. Numerous numerical and analytic (similarity solution) studies have shown a very strong dependence of ignition threshold on implosion velocity, on the order of 1./v**6. In single shell capsule design, the implosion velocity is set by the mass ablation rate of the pusher, and its residual mass near peak compression, both of which are constrained by driver energy. With a double shell design, conservation of momentum can be used to increase the inner shell velocity relative to the outer shell by choosing the mass (and diameter) of the inner shell. There are, of course, limits to how thin the inner shell can be made, dictated by hydrodynamic instabilities (both low and high mode number). In addition, since the outer shell material is still moving inward after collision, and shocks are generated by the collision, there are energy inefficiencies associated with double shell designs, which reduce the maximum Pdv work that can be done on the core fuel. These inefficiencies imply that a substantial decrease in fuel mass is necessary, typically an order of magnitude, relative to single shell designs. In order to increase the efficiency, most designs have some portion of the inner shell made from a relatively high-Z material that can trap radiation near peak compression. However, if the inner surface is made from high-Z material, then mixing can be very detrimental, due to ionization and radiative losses. The relatively high density of the high-Z material, coupled with the mix issues, have limited the velocity jump at collision to about 1.2 for the capsules discussed here.

The history of the double shell capsule in the ICF program had not been encouraging. The earliest double shell targets were shot at the Shiva laser (LLNL) in 1980 and at the GEKKO XII laser (ILE) in 1983. The measured yields for capsules designed with convergence > 30 were less than 1% of clean 1D calculations (YOC). The double shell concept fell from favor and lay dormant until recent years when Los Alamos reassessed the concept (Harris and Varnum, 1996), and began a series of experiments using the NOVA and Omega laser facilities. The first shots were at NOVA in 1998 using cylindrical hohlraums, and produced disappointing results with YOC again in the range of ~1%, indicating poor target performance. The belief at the time was that was that the thermal radiation environment produced by the NOVA laser beams was too poor to effectively drive the target. It was thought that the Omega laser had the potential to produce a much better thermal drive symmetry in a hohlraum than was the case in the NOVA hohlraum, so the next set of experiments was shifted to Omega.

The initial Omega experiments using double shells in spherical hohlraums with better drive uniformity produced nearly identical results to our earlier NOVA experiments, suggesting that the thermal radiation environment was perhaps not the main culprit in the failure of these implosions. An examination of the radiation drive in the Omega spherical hohlraum indicates that about 7% of the radiation power was actually in the Au M-band in the 2 to 2.5 keV photon energy range. This component of x-ray drive would be much more non-uniform than the thermal component, due to the localization of the M-band source at the laser hot spot locations. Because the M-band is more penetrating than the thermal component and can more easily affect the inner capsule, it was felt that the non uniform M-band may be a significant source of radiation asymmetry affecting both single and double shell implosions. A new double shell target was designed, with the intent of reducing the M-band radiation incident on the most unstable surface in the implosion, the outer surface of the inner capsule, or to remove in large part the material in the inner capsule capable of absorbing any M-band which is present. The former design was called the "suppressed M-band target" and the latter design is called the "reduced M-band absorption target". We have performed experiments at the Omega laser during 1999 and 2000 using these modified capsule designs in both spherical and cylindrical hohlraums with some striking successes.

2. Experimental Design and Results

The standard double shell target, which has performed poorly (YOC ~ few percent) both at NOVA and the Omega laser is illustrated in Figure 1. The capsule consists of a 76 µm thick CH ablator with outside radius of 275 µm. The inner shell consists of 23 µm thick glass layer. The shells are separated by a 30 mg/cc CH foam. The inner gas region is filled with 36 atm deuterium. This capsule may be extremely sensitive to asymmetric Mband radiation, and was redesigned to significantly modify the M-band transmitted to the inner capsule or to reduce the amount of M-band which can be absorbed by the material in the inner shell.

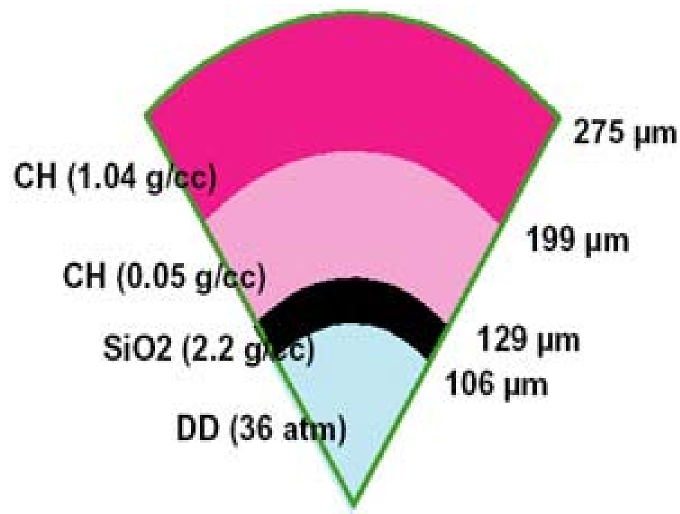

Figure 1: “standard” double shell design

These variants to the design are illustrated in Figure 2.

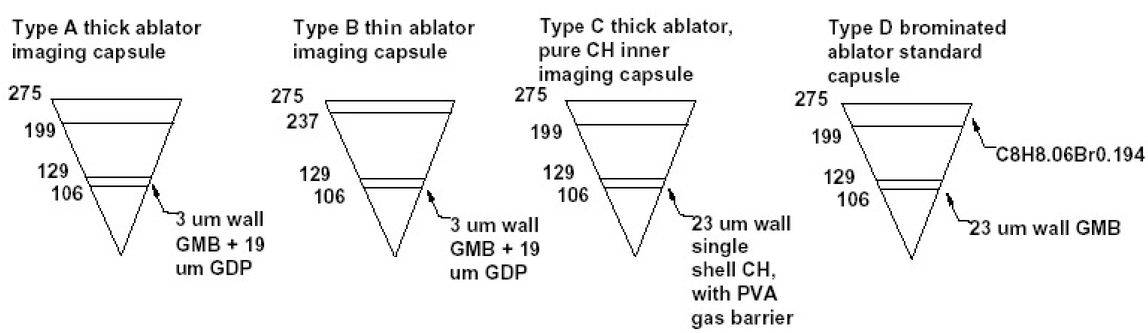

Figure 2: Double shell design variants Type A to Type D

The "imaging " capsule design is meant to reduce absorption of M-band by removing 80% of the glass in the inner shell and replacing it with a CH layer. Glass is a more effective absorber of M-band radiation than CH, so replacing the glass with CH reduces the overall M-band absorption in the inner shell. This also has the advantage in that the

imploded core emission can be imaged with x-ray cameras since the shell opacity is reduced. The Type-A thick ablator imaging capsule in Figure 2, is the normal imaging capsule with the 76 µm thick outer CH shell. The inner shell is composed of 3 µm glass overcoated with 20 µm CH. The Type-B thin ablator imaging capsule has a 38 µm outer CH shell and in 1D calculations, gives a much higher capsule yield. The Type-C pure CH imaging capsule is similar to Type-A, but the inner shell is 23 µm CH and all the glass has been removed. This further reduces the response of the inner capsule to any incident M-band radiation.
The Type-D suppressed M-band capsule is similar to the standard double shell with a 23 µm glass inner capsule, but the outer shell is now 76 µm of brominated CH. The brominated CH in the outer shell reduces the transmitted M-band to 15% of the undoped level.

The standard design and the Type-A imaging and the Type-D suppressed M-band designs were shot in spherical "tetrahedral" hohlraums with four laser entrance holes at the Omega laser during 1999 with some excellent results. The standard capsule with no M-band mitigation produced YOC ~ few percent as before. The capsule designed to reduce absorption of the M-band (Type-A imaging) gave neutron yield of YOC 40% and 60% in two shots at convergence 32. This was the first time such a high YOC was observed at such a high convergence. The Type-D suppressed M-band design showed improved result over the standard design with YOC of 5%, also at convergence of 32. These results were repeated in another experimental series using tetrahedral hohlraums at Omega during 1999 with similar good results. With this confirmation of an imaging double shell capsule operating at high YOC at convergence greater than that required for NIF ignition, it became important to determine whether the capsules would work well in a NIKF style cylindrical hohlraum. The most recent series of double shell shots in November, 2000, used cylindrical hohlraums at Omega to confirm the improved performance of reduced M-band absorption designs independent of hohlraum type. The double shell capsules showed continued excellent performance using cylindrical hohlraums at Omega, with YOC up to 100% for the imaging capsules. Figure 3 gives a summary of the YOC vs capsule convergence for the double shell database in cylindrical and tetrahedral hohlraums. The plot with the different variants of the target designs does indicate that the performance in either type of hohlraum is comparable. Although the results may have more speread than desired, the new pure CH imaging capsule worked well in NIF style cylindrical hohlraums with yields in good agreement with 1-dimensional calculations. The reduced absorption brominated ablator targets continued to perform poorly for unknown, possibly target defect, reasons.

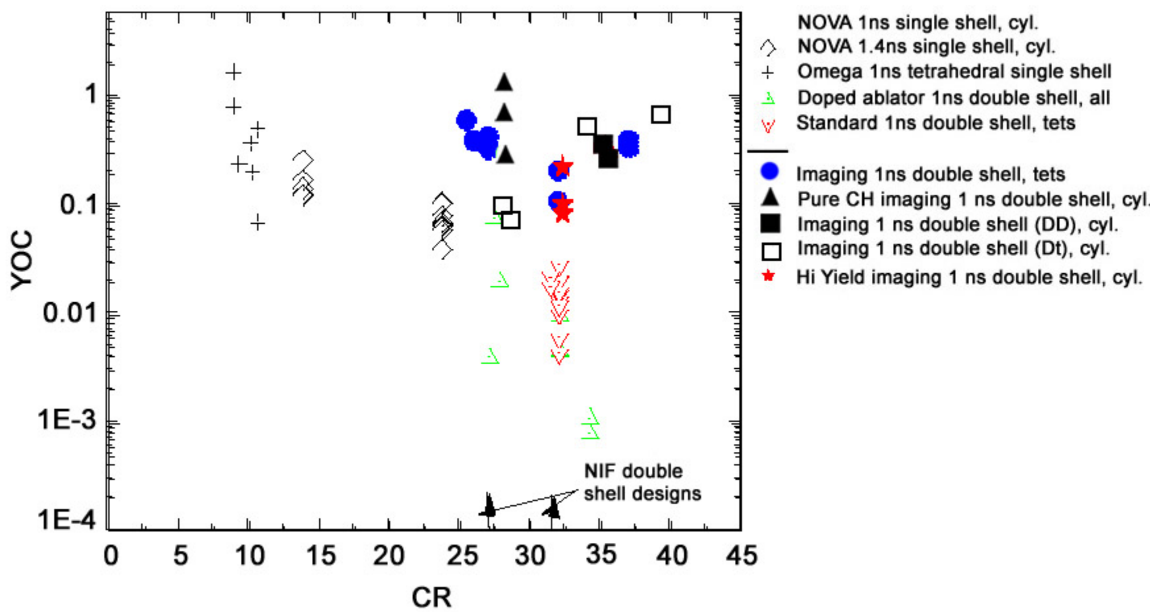

Figure 3: measured yield (YOC) vs capsule convergence

3. Conclusions

The type of hohlraum used for an indirect drive double shell implosion, given high quality targets and an imaging type capsule design, seems to be unimportant. Excellent capsule performance is achieved using either cylindrical or spherical hohlraums. The performance of the imaging double shell designs, regardless of whether or not they contain glass in the inner shell, seems to significantly exceed the performance of comparably sized single shell capsules (as measured by YOC). Both the pure CH and standard imaging designs approach clean 1D performance at calculated convergence ratios well beyond that required for an ignition double shell design to work at NIF energy levels. This means that the double shell concept remains a viable alternative to cryogenic single shell ignition target designs for NIF. The work reported here indicates, though not definitively, that asymmetric M-band radiation from gold in the hohlraum is probably a major cause for the poor performance of the standard thick glass double shell design which performed poorly in the initial double shell experiments. This work was performed under the auspices of the U.S. Department of Energy by the Los Alamos National Laboratory under contract No. W-7405-Eng-36.

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